

APPENDIX H

MARINE MAMMAL HEARING AND SENSITIVITY TO ACOUSTIC IMPACTS

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1. INTRODUCTION/OVERVIEW

Marine animals critically depend on sound to live, making and listening to it in various ways to perform various life functions. The ocean is a naturally noisy place, but humans make a host of sounds that are increasingly impinging on the ocean acoustic environment. There is clear evidence that some of these sounds can negatively impact marine life, but the types and magnitudes of impacts as they relate to different species and sound types remain poorly understood in all but a few conditions. However, there has been significant progress in the last decade, particularly in scientific knowledge in these areas, for some species and conditions, both in terms of hearing impacts and behavioral responses to various kinds of noise. From this evolution in understanding has emerged new ways of assessing and mitigating potential impacts. While much of the focus and discussion have been on potential injurious types of sound impacts (driven by concerns over hearing/tissue damage and the isolated mass strandings of beaked whales exposed to military sonar), more focus recently has been on the impacts of human noise on biologically significant behaviors and the overall acoustic ecology of marine life. There is a realization that the footprints within which direct harm may occur are relatively small, and the conditions in which marine mammals will become stranded appear to be restricted. However, the areas over which animals may be disturbed in significant ways that may impact vital life functions can be significantly larger. These considerations and the underlying complexity of understanding and assessing their probability of occurrence, as well as mitigation, have become more critical in noise exposure criteria and other means of assessment. Many of these issues and the underlying science are considered in detail in a major comprehensive review and application of science in the context of noise exposure criteria (Southall et al., 2007). That assessment forms the current basis for much of this appendix, but subsequent studies have provided additional important findings that are also summarized here.

This appendix summarizes the current state of scientific knowledge about the importance of sound and effects of noise on marine animals, with particular attention to marine mammals. It considers separately the effects of noise on physiology, hearing, communication, and behavior from a range of different impulsive and continuous sound sources. It also considers historical and emerging noise exposure criteria and operational mitigation measures, with attention to the types of acoustic sources present in the proposed geological and geophysical (G&G) operations off the U.S. East Coast. Finally, noise impacts for endangered/threatened species most likely to be present in these areas are considered.

2. ROLE OF ACOUSTICS IN MARINE MAMMAL ECOLOGY

The underwater acoustic environment can be a noisy place, receiving sound from a host of natural and anthropogenic sources. Some natural sounds are biological (e.g., fishes, marine mammals, some invertebrates), and others are environmental (e.g., waves, earthquakes, rain). Among the anthropogenic sources, many produce noise as a by-product of their normal operations (e.g., shipping, drilling, tidal turbines), whereas others (e.g., sonars, airguns) are produced for a specific remote sensing purpose (see Hildebrand [2009] for a recent review). Detailed measurements have been made for many of these sources, but their degree of overlap with and impacts on acoustically-oriented marine life remains generally poorly understood.

For most marine vertebrates, the production and reception of sound serves critical biological functions, including communication, foraging, navigation, and predator-avoidance (e.g., Schusterman, 1981; Watkins and Wartzok, 1985; Richardson et al., 1995; Tyack, 1998; Wartzok and Ketten, 1999; National Research Council [NRC], 2003; 2005; Clark and Ellison, 2004; Southall et al., 2007). As a general statement, all studied marine mammals produce sounds in a variety of inter- and intra-individual contexts, most associated with vital life functions as identified by the NRC (2005). As described below and shown in **Figure H-1** in comparison with some of the major human noise sources, each species group utilizes different frequency ranges.

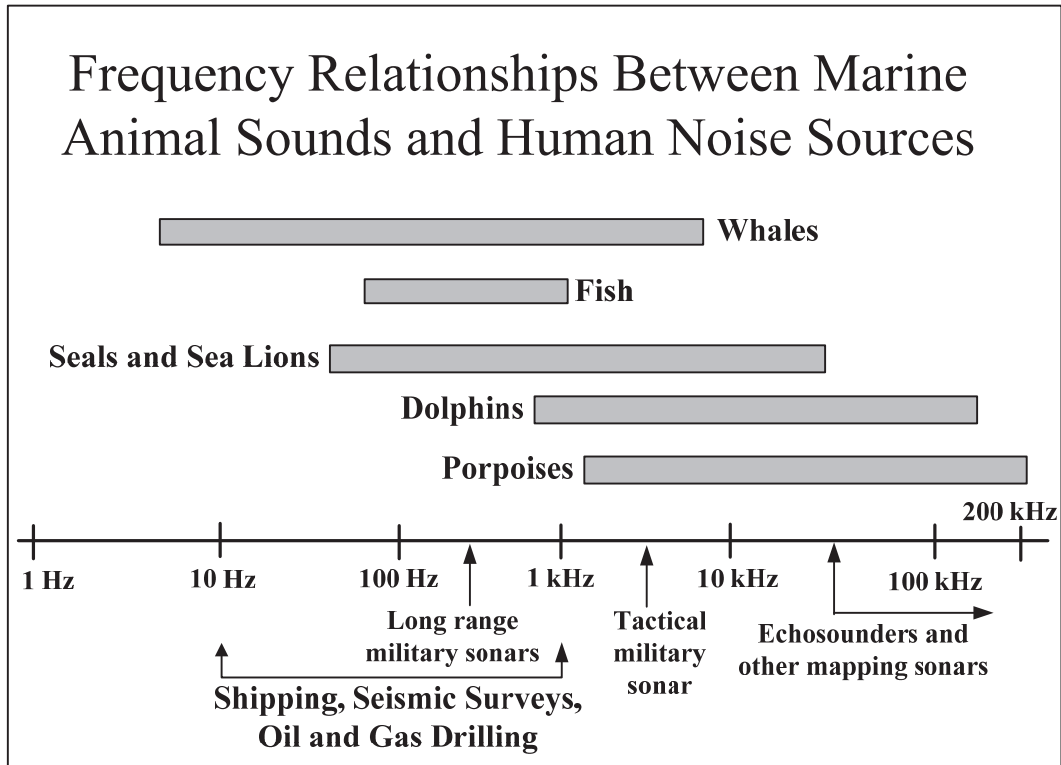


Figure H-1. Frequency Range of Sounds Generally Produced by Different Marine Animal Groups Shown Relative to Major Human Noise Sources.

Dolphins, porpoises, and other toothed whales (odontocete cetaceans) have developed sophisticated biosonar capabilities involving high frequency impulsive clicks to feed and navigate (Au, 1993) and use a variety of whistles and other calls to communicate in social interactions. These animals make sounds across some of the widest frequency bands that have been measured in any animal group. Communicative sounds generally range from a few hundreds of hertz to several tens of kilohertz, but echolocation clicks can extend above 100 kHz.

Baleen whales (mysticete cetaceans) have developed moderate to long-range communication capabilities for reproductive and social interactions and to orient themselves in the underwater world (e.g., Clark, 1990; Popper and Edds-Walton, 1997). Large whales generally produce low-frequency sounds in the tens of hertz to the several kilohertz band, with a few signals extending above 10 kHz.

Other marine mammals such as pinnipeds, manatees, and polar bears make and listen to sounds for a variety of communicative and spatial orientation functions, but like the large whales they appear to lack specialized echolocation capabilities (Schusterman, 1981; Schusterman et al., 2000). These sounds can extend above those used by mysticetes but occur over a narrower frequency band than those used by odontocetes, generally from ~100 Hz to several tens of kilohertz. Pinnipeds and polar bears spend time both at sea and on land, however, and thus rely on sounds both above and below the water.

Finally, many fishes make and listen to sounds in mating and other social interactions (Kaatz, 2002). Most of these sounds are generally low-frequency in nature, although some fishes produce more impulsive sounds as well. Aside from some simple hissing and other sounds produced in air, marine turtles generally do not appear to produce sounds in water for communicative or foraging purposes, but may rely on sound in a general orienting sense.

3. HEARING IN MARINE MAMMALS

Hearing has been measured using behavioral and/or electrophysiological methods in about a quarter of the known marine mammal species, although with a disproportional representation of species commonly found in captivity, and some entire groups (e.g., mysticete cetaceans) remain untested. For a detailed review, see Southall et al. (2007); key findings obtained since then are discussed below. Hearing sensitivity is generally quantified by determining the quietest possible sound that is detectable by an animal (either via a behavioral response or by quantifying an electrical response) on some signal presentations. By testing such responses across a range of test frequencies, a measure of the animal's overall hearing capability (typically called an “audiogram”) may be obtained; an example is given in **Figure H-2**.

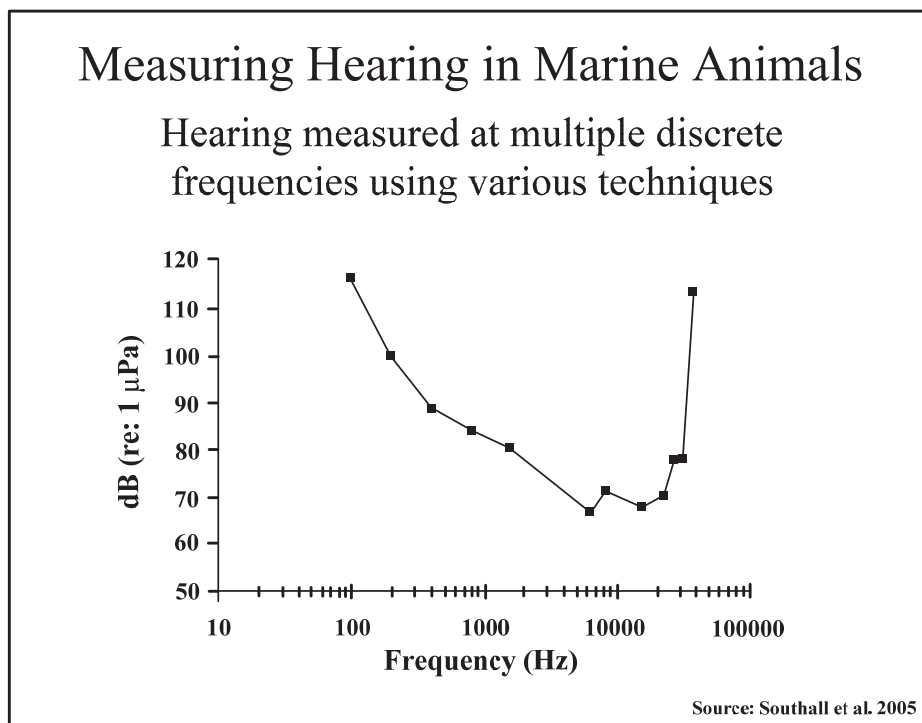


Figure H-2. Typical Hearing Curve or “Audiogram” Obtained from a California Sea Lion with a Behavioral Testing Technique.

Where detection threshold levels are lower, hearing sensitivity is greater (the animal can hear well), and vice versa. This sensitivity usually follows a U-shaped curve with regions of relatively good sensitivity that drop off on the low and high ends. The region of lowest overall average hearing is called the range of “best hearing sensitivity.” Similarly, the region where hearing thresholds are within some range from the lowest overall threshold (e.g., 80 dB in Southall et al., 2007) is often referred to as the overall range of functional hearing.

Given the available direct measurements of hearing, extrapolations based on taxonomy, and predictions based on auditory morphology, vocalizations, or behavior, it is clear that not all marine taxa have equal hearing frequency ranges or absolute hearing sensitivity (Richardson et al., 1995; Wartzok and Ketten, 1999; Southall et al., 2007).

As shown in **Figure H-3**, most marine taxa have measured or estimated (in the case of baleen whales) functional hearing capabilities across similar frequencies to those where their vocalizations occur, although perception may be slightly broader than the frequency range of vocalizations (Luther and Wiley, 2009). Fishes generally hear in a relatively narrow frequency band up to just a few kilohertz, while marine mammals as a whole cover a very wide band, with baleen whales likely hearing down into very

low frequencies, pinnipeds at low to intermediate frequencies (relatively), and odontocete cetaceans hearing over a very broad range extending well into the ultrasonic (for humans) range. Recently, functional hearing has been demonstrated in a marine invertebrate as well (longfin squid; see Mooney et al., 2010). Specific hearing characteristics for different marine mammal groups are described below.

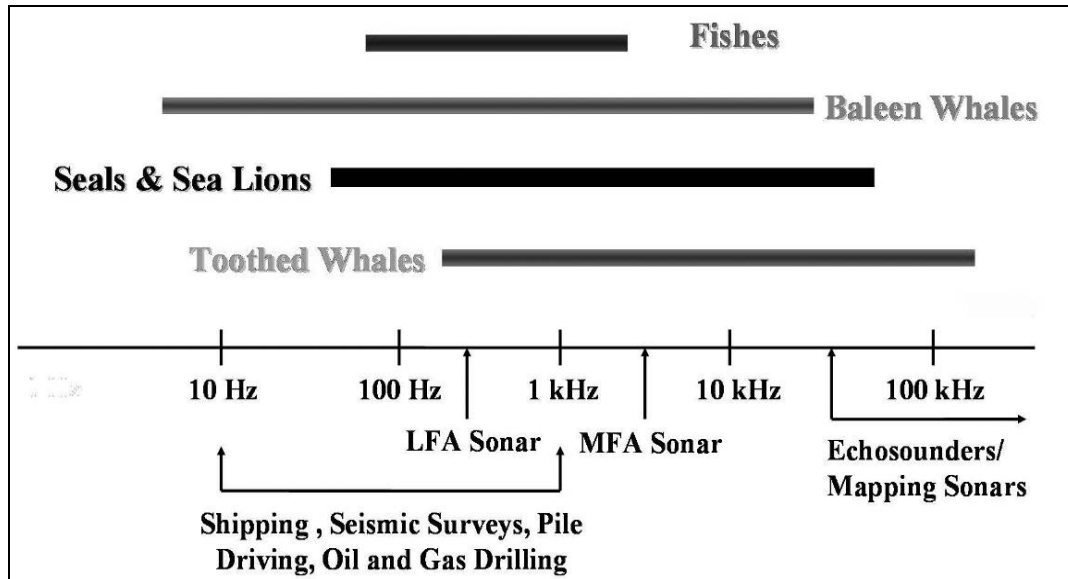


Figure H-3. Measured or Estimated Functional Hearing Ranges for Different Marine Vertebrate Groups Shown Relative to Various Human Noise Sources.

3.1. HEARING IN MYSTICETE CETACEANS

Because of the lack of captive subjects and logistical challenges of bringing experimental subjects into the laboratory, direct measurements of mysticete hearing are unavailable, although there was an unsuccessful attempt to directly measure hearing in a stranded gray whale calf by Ridgway and Carder (2001). Consequently, hearing in mysticetes is estimated based on other means such as vocalizations (Wartzok and Ketten, 1999), anatomy (Houser et al., 2001; Parks et al., 2007), behavioral responses to sound (Frankel, 2005; Reichmuth, 2007), and nominal natural background noise conditions in the likely frequency ranges of hearing (Clark and Ellison, 2004).

The combined information from these and other sources strongly suggests that mysticetes are likely most sensitive to sound from perhaps tens of hertz to ~10 kHz. However, humpback whales (*Megaptera novaeangliae*) produce sounds with harmonics extending above 24 kHz (Au et al., 2006), and Ketten et al. (2007) suggested, based on anatomical data, that some mysticetes could hear frequencies up to 30 kHz. Southall et al. (2007) estimated the lower and upper frequencies for functional hearing in mysticetes, collectively, to be 7 Hz and 22 kHz, respectively, but based on the above information this may be a slight underestimate on the high frequency cutoff. Nevertheless, there appears to be little doubt that mysticetes operate primarily in the very low and low frequency ranges.

3.2. HEARING IN ODONTOCETE CETACEANS

Because of the presence of specialized, high frequency biosonar and lower frequency communication systems in odontocete cetaceans, it is almost certain that they hear over an extremely wide frequency range, spanning some 12 octaves in some species. Hearing has been directly measured in controlled conditions for over a dozen odontocete species with either behavioral or electrophysiological techniques. Southall et al. (2007) reviewed the available literature and (like Wartzok and Ketten [1999]) identified two functional hearing groups within the odontocetes, which they referred to as mid-frequency cetaceans

(with functional hearing between 150 Hz and 160 kHz) and high-frequency specialists (functional hearing estimated between 200 Hz and 180 kHz). Subsequent to the Southall et al. (2007) publication, additional data have been obtained on several species that had been previously tested (such as harbor porpoise) and measurements or anatomical modeling results have been obtained for several new species – e.g., Cuvier's beaked whales (Cranford et al., 2008a,b) and false killer whales (Montie et al., 2011) suggesting that these additional species have similar basic hearing ranges and functional capabilities to other cetaceans. These and other studies have contributed to an increased understanding of hearing in odontocete cetaceans, but they are fundamentally consistent for these species with the Southall et al. (2007) assessment for these species in terms of the broad range and high-frequency extension of functional hearing in odontocete cetaceans.

3.3. HEARING IN PINNIPEDS AND MANATEES

Pinnipeds are amphibious mammals and have functional hearing both above and below the water, although they have broader functional hearing ranges in water (Kastak and Schusterman, 1998 for a discussion). Direct measurements of hearing using behavioral and electrophysiological methods have been obtained in nearly 10 different species (Southall et al., 2007; Mulsow and Reichmuth, 2010). Southall et al. (2007) estimated functional hearing across all pinnipeds as extending between 75 Hz and 75 kHz under water and between 75 Hz and 30 kHz in air. However, they also noted that, as in the odontocete cetaceans, there appears to be a segregation in functional hearing within pinniped taxa, with phocids (seals lacking external ear pinnae that are less mobile on land, such as harbor seals) extending to much higher frequencies, especially in water, than otariids (seal lions and fur seals that have distinct external ear pinnae and are more agile on land). This would be a logical additional segregation in terms of functional hearing within marine mammals.

Hearing has also been tested both in terms of absolute and masked hearing capabilities in manatees (Gerstein et al., 1999; Mann et al., 2005). The combined data suggest that manatees have hearing capabilities that are generally similar to phocid pinnipeds except perhaps at the lowest frequencies, with functional hearing between about 250 Hz and ~80 kHz. Based on these data, the extrapolation of pinniped data to manatees, where information is lacking, would seem reasonable.

3.4. MARINE MAMMAL HEARING WEIGHTING FUNCTIONS

Because animals including marine mammals do not hear equally well at all frequencies, frequency-weighting functions are often used as a means of quantitatively compensating for differential frequency responses for different species. These are commonly applied in assessing the potential for the detection of a sound at a specific frequency and, more commonly, for assessing potential noise impacts. Noise exposure criteria are discussed in greater detail in **Section 4.0**. However, as they are related to the above generalizations regarding basic hearing in different marine mammal groups, the frequency weighting functions derived by Southall et al. (2007) are described briefly here.

Table H-1 shows the five functional hearing groups and estimated functional hearing ranges for marine mammals proposed in the Southall et al. (2007) noise exposure criteria.

Using the estimated lower and upper frequency cut-off limits as 6-dB down points on an exponential roll-off for the frequency-weighting functions (as is done in human C-weighting), Southall et al. (2007) developed frequency-weighting filters for each of the five functional hearing groups as shown in **Figure H-4**.

Table H-1

Marine Mammal Functional Hearing Groups and Estimated Functional Hearing Ranges
Proposed by Southall et al. (2007)

| Functional Hearing Group | Estimated Auditory Bandwidth | Genera Represented (Number Species/Subspecies) | Frequency-Weighting Network |
|--------------------------|------------------------------|--|--|
| Low-frequency cetaceans | 7 Hz to 22 kHz | <i>Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera</i> (13 species/subspecies) | M_{lf} (lf: low-frequency cetaceans) |
| Mid-frequency cetaceans | 150 Hz to 160 kHz | <i>Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcacella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon</i> (57 species/subspecies) | M_{mf} (mf: mid-frequency cetaceans) |
| High-frequency cetaceans | 200 Hz to 180 kHz | <i>Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus</i> (19 species/subspecies) | M_{hf} (hf: high-frequency cetaceans) |
| Pinnipeds in water | 75 Hz to 75 kHz | <i>Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarcots, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, Odobenus</i> (41 species/subspecies) | M_{pw} (pw: pinnipeds in water) |
| Pinnipeds in air | 75 Hz to 30 kHz | Same species as pinnipeds in water (41 species/subspecies) | M_{pa} (pa: pinnipeds in air) |

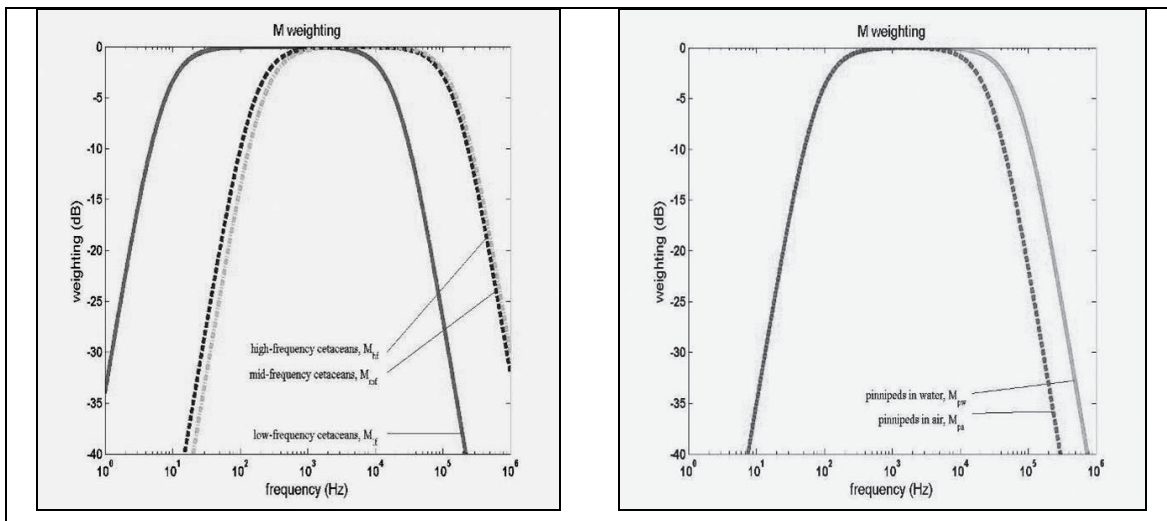


Figure H-4. Frequency-Weighting Functions for Cetaceans (left) and Pinnipeds in Air and Water (right) Proposed by Southall et al. (2007).

4. EFFECTS OF NOISE ON MARINE MAMMAL HEARING AND BEHAVIOR

Where there is an overlap between noise sources and the frequencies of sound used by marine life, there may be concerns related to how such sound may interfere with important biological functions. Noise, either natural or anthropogenic, can adversely affect marine life in various ways, inducing alteration of behavior, reduction of communication ranges or orientation capability, temporary or permanent damage to the auditory or other systems; and/or, in extreme cases, habitat avoidance or even death (e.g., Richardson et al., 1995; NRC, 2003, 2005; Nowacek et al., 2007; Southall et al., 2007). Noise impacts may also be additive or synergistic to those of other human stressors. While determining the biological significance of noise exposure impacts remains challenging (NRC, 2005), significant strides have been made in quantifying the effects of noise on marine mammals. The potential and measured effects of noise on physiology, hearing, and behavior are reviewed here, with attention to findings subsequent to the Southall et al. (2007) review and assessment of noise impacts on marine mammals.

4.1. EFFECTS OF NOISE ON MARINE MAMMAL PHYSIOLOGY

Noise can result in direct, physiological impacts on marine mammals, even in cases where hearing impacts or even behavioral responses may be lacking. These may include stress responses and direct physical injury (e.g., tissue damage). Stress responses can vary from an acute startle response to more chronic effects and can vary widely across individuals in type and magnitude according to a host of factors (Busch and Hayward [2009] for a recent review). Stress reactions in humans and other vertebrates include various physiological changes to pulmonary, respiratory cardiac, metabolic, neuro-endocrine, immune, and reproductive functions; these can vary from relatively benign to very detrimental or fatal in some conditions.

Direct measurements of physical stress responses in marine mammals from sound exposure are relatively limited (Thomas et al., 1990; Miksis et al., 2001; Romano et al., 2004), although the larger body of data for terrestrial mammals and other animals is available and, in some cases, may be useful where direct information is lacking (Wright et al., 2007a,b). The available literature for marine mammals indicates endocrine secretions of glucocorticoids and altered cardiovascular function in some conditions following relatively intense noise exposure.

Direct physical injury can occur from exposure to high levels of sound or, more commonly, to shock wave pulses associated with high intensity events such as explosions. These pulses are typically short, peak pressures that may damage internal organs or air-filled body cavities, such as lungs (Yelverton et al., 1973; Goertner, 1982; Young, 1991). Direct data on direct physical injury are limited to anecdotal or forensic investigations after accidental events because ethical considerations prevent direct empirical methods to measure such impacts in marine mammals. However, such observations (e.g., Todd et al., 1996) and modeling based on impact data for the human vestibular system as well as other organs (e.g., lungs) for underwater sound exposures (Cudahy and Ellison, 2002) suggest that marine mammals can be susceptible to direct physical injury to particular organ systems and tissues following intense exposure, particularly where high particle motion events occur.

Other forms of physiological damage that have been investigated and in some cases shown in marine mammals include the formation of gas bubble lesions and fat emboli, similar to those associated with human decompression sickness; these have been observed in some beaked whale species that stranded around naval mid-frequency sonar training exercises (Jepson et al., 2003; Fernández et al., 2005). Currently, these tissue impacts are thought to result from a behavioral response that changes diving patterns in some way and subsequently causes lesion/emboli formation, rather than as a direct physical effect of sound exposure (Cox et al., 2006; Zimmer and Tyack, 2007). These kinds of emboli have not been definitively shown in other marine mammals exposed to natural or anthropogenic sound to date.

4.2. EFFECTS OF NOISE ON MARINE MAMMAL HEARING

Much of the scientific and regulatory attention on the impacts of noise on marine life has centered on the issue of how sound affects hearing in marine mammals. While the available literature on the

underlying issues remains quite limited compared to that available for some terrestrial species, considerable progress has been made in these areas, particularly in the last decade, for marine mammals. There have been numerous reviews of the available data on these issues (Richardson et al., 1995; Wartzok and Ketten, 1999; NRC, 2003, 2005), the most recent comprehensive assessment being the Southall et al. (2007) review and application of the available science in the context of proposing noise exposure criteria (see below). A summary description of temporary and permanent hearing losses and auditory masking is given here with reference to these reviews generally, and some discussion of more recent relevant literature on each issue.

4.2.1. Temporary and Permanent Threshold Shift in Marine Mammals

Noise-induced threshold shifts are increases in hearing thresholds within a certain frequency range (Yost, 2000). Following exposure, the magnitude of the threshold shift normally decreases over time following cessation of noise exposure. Threshold shifts can be temporary (TTS) or permanent (PTS) and can consist of both temporary and permanent components. Several important factors relate to the type and magnitude of hearing loss, including exposure level, frequency content, duration, and temporal pattern of exposure. A range of mechanical stress or damage (e.g., supporting cell structure fatigue) and metabolic (e.g., inner ear hair cell metabolism, such as energy production, protein synthesis, and ion transport) processes within the auditory system underlie both TTS and PTS (Yost, 2000; Kryter, 1994; Ward, 1997). Intense sound exposure more often results in mechanical processes, whereas prolonged exposure more typically results in metabolic changes (e.g., Saunders et al., 1985).

Temporary threshold shift is a relatively short-term reversible loss of hearing, often resulting from cellular fatigue and metabolic changes. Based on data from cetacean TTS studies (Southall et al., 2007), a threshold shift of 6 dB is generally considered the minimum threshold shift that is statistically larger than typical day-to-day or session-to-session variation in a subject's baseline threshold at a particular frequency. Conversely, PTS is an irreversible loss of hearing (permanent damage) that commonly results from inner ear hair cell loss and/or severe damage or other structural damage to auditory tissues (e.g., Saunders et al., 1985; Henderson et al., 2008). Permanent threshold shift data are typically not collected in marine mammals owing to ethical and permitting reasons, but a recent TTS experiment was found to unintentionally induce PTS in a harbor seal (Kastak et al., 2008). Southall et al. (2007) reviewed the available terrestrial literature and concluded that 40 dB of TTS was a reasonable and conservative approximation of PTS onset for marine mammals (Henderson et al., 2008 for a consideration of the human literature in this regard).

Temporary threshold shift has been measured in three cetacean and three pinniped species using both impulsive and continuous noise; many of these data were reviewed in detail by Southall et al. (2007), but there are some notable new data that change some of the conclusions reached in that assessment. In general, it appears that marine mammal auditory systems are relatively resilient to noise exposure and that relatively intense sounds are required to cause TTS and, given some simplifying assumptions to extrapolate to 40 dB TTS, PTS as well. However, there are clear differences in terms of the sound exposure types and some major differences between species as well. As in terrestrial mammals, marine mammals experience TTS at relatively lower onset levels for impulsive noise than for non-impulsive noise. The relative TTS onset levels for different marine mammal groups from the Southall et al. (2007) criteria are discussed in the section below regarding exposure criteria. However, some modifications to these criteria would now be in order, as expected, based on subsequent information.

New data are available demonstrating much lower (>20 dB) TTS-onset exposure levels for harbor porpoises exposed to impulse noise (airguns) than has been measured in other odontocetes (Lucke et al., 2009). These data are significant because they are the only TTS measurements available for any individual in the high-frequency cetacean functional hearing group and would arguably be used as the representative value for these species rather than using the extrapolated (though much more expansive) data for mid-frequency cetaceans in predicting auditory fatigue. In addition, several studies have contributed to an expanded understanding of TTS onset and growth at a range of sound frequencies in odontocete cetaceans. Mooney et al. (2009a,b) demonstrate conditions where equal energy assumptions about exposure of different durations and levels fail to accurately predict TTS onset and growth. Finneran and Schlundt (2010) and Finneran et al. (2010a,b) provide additional TTS data for bottlenose

dolphins, demonstrating a greater sensitivity (10-20 dB) to noise exposure (lower absolute TTS onset levels) and a more rapid growth of TTS with increasing noise exposure level at higher frequencies within their region of best sensitivity than had been tested when the Southall et al. (2007) criteria were published. These data suggest that the exposure level relative to the subject's absolute hearing sensitivity (referred to as the sensation level) is particularly important in determining TTS onset. They also suggest that exposure levels in the region of best hearing sensitivity should be used as generic TTS-onset values against which frequency weighting functions could be applied to correct for frequency-specific hearing. These findings are significant for mysticetes despite being made with odontocete cetaceans, as they affect the selection of the appropriate TTS-onset values to apply for mysticetes from the odontocete literature (since no mysticete TTS values are or for the foreseeable future will be available).

4.2.2. Auditory Masking

In addition to potential effects on hearing from relatively high levels of sound exposure that would generally occur relatively close to anthropogenic sound sources in the field, noise interference (“masking”) effects can occur, and likely do over much greater footprints around real sound sources. Noise can affect hearing and partially or completely reduce an individual's ability to effectively communicate, detect important predator, prey, and/or conspecific signals, and/or detect important environmental features associated with spatial orientation (Clark et al., 2009 for a review). Spectral, temporal, and spatial overlap between the masking noise and the sender/receiver determine the extent of interference; the greater the spectral and temporal overlap, the greater the potential for masking.

Southall et al. (2007) considered auditory masking issues and realized the much greater relative areas over which this phenomena occurs relative to TTS and PTS, but did not propose explicit exposure criteria for marine mammals, owing in part to the very divergent conditions in which masking can occur and a lack of clear understanding about defining an “onset” for masking that would be statistically definable and biologically meaningful. Largely for the same reasons, masking effects have generally been considered only qualitatively in planning of activities and regulatory decisions over noise impacts. Subsequent data have demonstrated vocal modifications in marine mammals exposed to noise that are presumably the result of anthropogenic masking noise (e.g., Holt et al., 2009). Additionally, Clark et al. (2009) provided a quantitative means of determining the relative loss of acoustic communication range for marine mammals using specific calls in conditions where they are exposed to specific anthropogenic noise sources.

There is particular concern that low-frequency anthropogenic noise may mask communication in baleen whales, which can communicate over long distances and within the same frequency band (e.g., Payne and Webb, 1971; Clark et al., 2009). An example of baleen whale calling behavior that is increasingly masked by nearby ship noise is shown in **Figure H-5**.

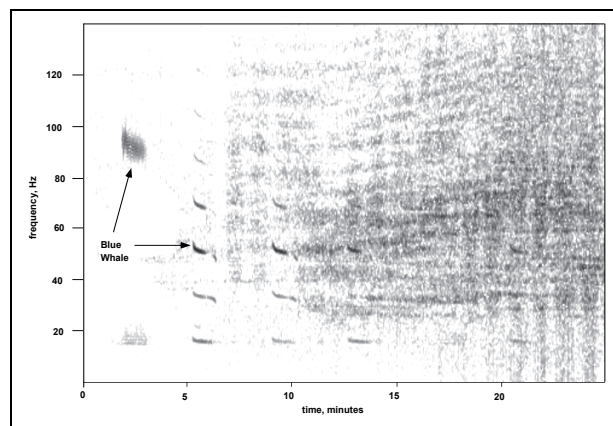


Figure H-5. Time Series Plot Showing a Calling Blue Whale and the Increasing Noise (and Masking) in the Same Low-Frequency Band from an Approaching Vessel (courtesy of C. Clark).

4.3. EFFECTS OF NOISE ON MARINE MAMMAL BEHAVIOR

Behavioral responses to sound are highly variable and critically depend on the context of sound exposure, as much or more than the level-duration-frequency characteristics that determine the probability of auditory effects (Wartzok et al., 2004, Southall et al., 2007). There is a very wide range of possible behavioral responses to sound exposure, given that the sound is audible to the particular animal, including, in approximate order of increasing severity but decreasing likelihood:

- none observable – animals can become less sensitive over repeated exposures;
- looking or increased alertness;
- minor behavioral responses such as vocal modifications associated with masking;
- cessation of feeding or social interactions;
- temporary avoidance behavior (emerging as one of the more common responses);
- modification of group structure or activity state;
- habitat abandonment; and/or
- injury and/or death via direct response or possibly exacerbated by physiological factors.

These effects clearly have differing probabilities to affect marine mammal vital rates (NRC, 2005), but it has proven (and remains) exceedingly difficult to establish a generally accepted definition and criterion for biologically meaningful behavioral disturbance. Assessing the severity of behavioral effects of anthropogenic sound exposure on marine mammals presents unique challenges associated with the inherent complexity of behavioral responses and the contextual factors affecting them, both within and between individuals and species. Severity of responses can vary depending on characteristics of the sound source (e.g., moving or stationary, number and spatial distribution of sound source[s], similarity to predator sounds, and other relevant factors) (Richardson et al., 1995; NRC, 2005; Southall et al., 2007; Wirsing et al., 2008; Bejder et al., 2009; Barber et al., 2010).

Southall et al. (2007) reviewed the considerable available literature on the effects of noise on marine mammal hearing in extensive detail, but (other than for single impulse exposures where TTS-onset was used as a threshold value for behavioral disturbance) did not find a single metric or identifiable exposure level that was broadly applicable as a benchmark for behavioral effects. Several general observations were made, including that many of the responses observed across taxa were temporary avoidance behavior. Additionally, certain species (e.g., harbor porpoises, beaked whales) appear to be categorically more sensitive to noise than other species observed, and certain behavioral states (e.g., migrating) can make species such as bowhead whales more sensitive to exposure. Subsequent data have demonstrated and quantified behavioral responses of various species, including some of the Endangered Species Act-listed marine mammals being considered in this Programmatic Environmental Impact Statement (Programmatic EIS), to seismic exploration using airguns (Weir, 2008a,b; Miller et al., 2009). Additional data have demonstrated behavioral responses of cetaceans to vessels associated with whale-watching activities (e.g., Bejder and Lusseau, 2008; Visser et al., 2010) and to the construction of offshore energy installations (Thompson et al., 2010). Finally, there has been considerable new information, using both controlled exposure experiments and opportunistic observations of anthropogenic noise source operations, on the behavioral responses of particularly sensitive marine mammals, including harbor porpoises (Kastelein et al., 2008a,b; Gilles et al., 2009) and beaked whales (Caretta et al., 2008; McCarthy et al., 2011; Southall et al., 2011; Tyack et al., 2011). These studies amplify the conclusions of Southall et al. (2007) that these are particularly sensitive species, although it remains unclear whether any additional species should be added to this general category.

5. MARINE MAMMAL NOISE EXPOSURE CRITERIA

Beginning in the 1980's with regulations on oil and gas exploration, sound-producing entities and regulatory agencies have been grappling with how to quantitatively predict and operationally mitigate the effects of human noise from industrial activities on marine life. While the marine noise issue is an increasingly global one, many of the developments on exposure criteria for marine mammals have involved U.S. regulatory processes.

In June 1997, the High Energy Seismic Survey team (HESS, 1999) convened a panel of experts to assess existing data on marine mammals exposed to seismic pulses and to predict exposures at which physical injury could occur. With the limited available data at that time, exposure to airgun pulses with received levels above 180 dB *re*: 1µPa (root-mean-square [RMS] – averaged over the pulse duration) was determined to have a high potential for “serious behavioral, physiological, and hearing effects.”

Based on the HESS (1999) panel conclusions, the National Marine Fisheries Service (NMFS) established a 180 dB_{rms} (received level) threshold criterion for injury from sound exposure for cetaceans and a 190 dB_{rms} threshold criterion for pinnipeds (*Federal Register*, 2003). Additionally, behavioral response criteria were developed as step-function (all-or-none) thresholds based solely on the RMS value of received levels, and have been used by NMFS, although not entirely consistently. Thresholds for behavioral response from impulse sounds are 160 dB_{rms} (received level) for all marine mammals, based on behavioral response data for marine mammals exposed to seismic airgun operations (Malme et al., 1983, 1984; Richardson et al., 1986). Thresholds for behavioral response for “continuous” (non-impulsive) sounds have been 120 dB_{rms} (for some but not all sound sources) based on the results of Malme et al. (1984) and Richardson et al. (1990).

Recognizing that the available data on hearing and noise impacts were rapidly evolving and that a more comprehensive and scientifically robust method of assessment would be required than these simplistic threshold estimates, NMFS supported an expert working group to develop more comprehensive and current marine mammal noise exposure criteria. This process ultimately resulted in the Southall et al. (2007) marine mammal noise exposure criteria. Within this process, several important segregations were made. First, the marine mammals were segregated into the functional hearing groups (not entirely taxonomy-based), as described above. Second, sound sources were categorized into functional categories, based on their acoustic and repetitive properties (**Table H-2**).

Table H-2

Sound Source Categories, Acoustic Characteristics, and Examples, as Proposed by Southall et al. (2007)

| Sound Type | Acoustic Characteristics (at source) | Examples |
|----------------|---|--|
| Single Pulse | Single acoustic event; >3 dB difference between received level using impulse versus equivalent continuous time constant | Single explosion; sonic boom; single airgun, watergun, pile strike, or sparker pulse; single ping of certain sonars, depth sounders, and pingers |
| Multiple Pulse | Multiple discrete acoustic events within 24 hr; >3 dB difference between received level using impulse versus equivalent continuous time constant | Serial explosions; sequential airgun, watergun, pile strikes, or sparker pulses; certain active sonar (IMAPS); some depth sounder signals |
| Non-Pulse | Single or multiple discrete acoustic events within 24 h; <3 dB difference between received level using impulse versus equivalent continuous time constant | Vessel/aircraft passes, drilling; many construction or other industrial operations; certain sonar systems (LFA; tactical mid-frequency); acoustic harassment/deterrent devices; acoustic tomography sources (ATOC); some depth sounder signals |

IMAPS = Integrated Marine Mammal Monitoring and Protection System.

LFA = Low-Frequency Active.

ATOC = Acoustic Thermometry of Ocean Climate.

Additionally, the potential for hearing and behavioral effects for noise exposures of these different categories was assessed for each of the different functional hearing groups according to a wider and more applicable set of acoustic exposure metrics. For hearing impacts, this included the sound energy (sound exposure level), which accounts for amplitude level and duration, as well as peak sound pressure. For

behavioral effects, the conventional RMS levels for sound exposure were considered, in part because this is typically all of the information available regarding available studies.

As described briefly above, Southall et al. (2007) proposed explicit and numerical exposure level values for injury from sound exposure for each of the marine mammal functional hearing groups. Using measured onset-TTS levels where possible (or extrapolating them from related species where not) and a series of extrapolation procedures to estimate the growth of TTS and a reasonably conservative estimate of physical injury (40 dB TTS as described above), received level threshold values were determined. For sound exposure level values, the frequency weighting functions described above would be applied to the received sound to account for differential frequency sensitivity among the different marine mammal groups. The resulting thresholds for injury from sound exposure for different marine mammal groups, via these general methods and using all available relevant data as proposed by Southall et al. (2007), are summarized in **Table H-3**.

Table H-3

Marine Mammal Noise Exposure Criteria for Injury for Different Marine Mammal Functional Hearing Groups
Proposed by Southall et al. (2007)

| Marine Mammal Group | Sound Type | | |
|---------------------------------|--|--|--|
| | Single Pulses | Multiple Pulses | Non-Pulses |
| Low-frequency Cetaceans | Cell 1 | Cell 2 | Cell 3 |
| Sound Pressure Level | 230 dB _{peak} re: 1 μPa (flat) | 230 dB _{peak} re: 1 μPa (flat) | 230 dB _{peak} re: 1 μPa (flat) |
| Sound Exposure Level | 198 dB re: 1 μPa ² -s (M _{lf}) | 198 dB re: 1 μPa ² -s (M _{lf}) | 215 dB re: 1 μPa ² -s (M _{lf}) |
| Mid-frequency Cetaceans | Cell 4 | Cell 5 | Cell 6 |
| Sound Pressure Level | 230 dB _{peak} re: 1 μPa (flat) | 230 dB _{peak} re: 1 μPa (flat) | 230 dB _{peak} re: 1 μPa (flat) |
| Sound Exposure Level | 198 dB re: 1 μPa ² -s (M _{mf}) | 198 dB re: 1 μPa ² -s (M _{mf}) | 215 dB re: 1 μPa ² -s (M _{mf}) |
| High-frequency Cetaceans | Cell 7 | Cell 8 | Cell 9 |
| Sound Pressure Level | 230 dB _{peak} re: 1 μPa (flat) | 230 dB _{peak} re: 1 μPa (flat) | 230 dB _{peak} re: 1 μPa (flat) |
| Sound Exposure Level | 198 dB re: 1 μPa ² -s (M _{hf}) | 198 dB re: 1 μPa ² -s (M _{hf}) | 215 dB re: 1 μPa ² -s (M _{hf}) |
| Pinnipeds (in water) | Cell 10 | Cell 11 | Cell 12 |
| Sound Pressure Level | 218 dB _{peak} re: 1 μPa (flat) | 218 dB _{peak} re: 1 μPa (flat) | 218 dB _{peak} re: 1 μPa (flat) |
| Sound Exposure Level | 186 dB re: 1 μPa ² -s (M _{pw}) | 186 dB re: 1 μPa ² -s (M _{pw}) | 203 dB re: 1 μPa ² -s (M _{pw}) |
| Pinnipeds (in air) | Cell 13 | Cell 14 | Cell 15 |
| Sound Pressure Level | 149 dB _{peak} re: 20 μPa (flat) | 149 dB _{peak} re: 20 μPa (flat) | 149 dB _{peak} re: 20 μPa (flat) |
| Sound Exposure Level | 144 dB re: (20 μPa) ² -s (M _{pa}) | 144 dB re: (20 μPa) ² -s (M _{pa}) | 144.5 dB re: (20 μPa) ² -s (M _{pa}) |

Several notable features of these criteria are the relatively high received level values predicted necessary to induce injury and that all of the cetaceans have numerically-identical threshold values, with the exception of the frequency-weighting functions. The former is simply a function of the relatively high TTS-onset values in the marine mammal species tested thus far. The latter is the case because at the time of the Southall et al. (2007) criteria paper, there were no direct data on auditory fatigue in low- or high-frequency cetaceans, and the mid-frequency cetacean TTS-onset levels were used for these other groups. Subsequently, the Lucke et al. (2009) results have shown significantly lower onset values for TTS in high-frequency cetaceans; these will presumably be applied for these species. For low-frequency cetaceans, some of the subsequent TTS data for mid-frequency cetaceans in regions of best sensitivity (Finneran and Schlundt, 2010) may be applicable in considering the appropriate TTS-onset value to extrapolate to the mysticetes, which are highly unlikely to test in a controlled hearing study to measure auditory fatigue. Finally, these newer TTS measurements in mid-frequency cetaceans (Finneran and Schlundt, 2010; Finneran et al., 2010a,b) will require reanalysis of the appropriate TTS-onset (and thus injury onset) point for this category as well. Such improvements based on additional data were envisioned, and in most cases specifically called for in terms of experimental approaches and priorities, and the conclusions and threshold values will continue to evolve over time. Despite the expected requisite re-thinking based on new data, the Southall et al. (2007) approach to marine mammal noise

exposure represented a major evolution in the complexity and scientific basis for predicting the effects of noise on hearing in marine mammals over the extremely simplistic historical NMFS thresholds for injury.

In terms of behavioral impacts, the Southall et al. (2007) noise exposure criteria took a dual approach depending on the sound type. For exposure to single impulses (e.g., explosion), the acoustic component of the event was considered sufficiently intense to constitute behavioral harassment at levels consistent with TTS onset (**Table H-4**). The logic for this was that since these events are so brief and transient that any responses other than those affecting hearing would likely be similarly transient in nature and thus not affect the long-term health or fitness of animals. It was noted, however, that startle responses can trigger stress and other physiological responses, the biological significance of which remains poorly understood.

Table H-4

Marine Mammal Noise Exposure Criteria for Behavior for Different Marine Mammal Functional Hearing Groups Proposed by Southall et al. (2007)

| Marine Mammal Group | Sound Type | | |
|---------------------------------|--|---|---|
| | Single Pulses | Multiple Pulses | Non-Pulses |
| Low-frequency Cetaceans | Cell 1 | Cell 2 | Cell 3 |
| Sound Pressure Level | 224 dB _{peak} re: 1 μPa (flat) | see Tables 6 & 7 in Southall et al., 2007 | see Tables 14 & 15 in Southall et al., 2007 |
| Sound Exposure Level | 183 dB re: 1 μPa ² -s (M _{lf}) | Not applicable | Not applicable |
| Mid-frequency Cetaceans | Cell 4 | Cell 5 | Cell 6 |
| Sound Pressure Level | 224 dB _{peak} re: 1 μPa (flat) | see Tables 8 & 9 in Southall et al., 2007 | see Tables 16 & 17 in Southall et al., 2007 |
| Sound Exposure Level | 183 dB re: 1 μPa ² -s (M _{mf}) | Not applicable | Not applicable |
| High-frequency Cetaceans | Cell 7 | Cell 8 | Cell 9 |
| Sound Pressure Level | 224 dB _{peak} re: 1 μPa (flat) | see Tables 18 & 19 in Southall et al., 2007 | see Tables 18 & 19 in Southall et al., 2007 |
| Sound Exposure Level | 183 dB re: 1 μPa ² -s (M _{hf}) | Not applicable | Not applicable |
| Pinnipeds (in water) | Cell 10 | Cell 11 | Cell 12 |
| Sound Pressure Level | 212 dB _{peak} re: 1 μPa (flat) | see Tables 10 & 11 in Southall et al., 2007 | see Tables 20 & 21 in Southall et al., 2007 |
| Sound Exposure Level | 171 dB re: 1 μPa ² -s (M _{pw}) | Not applicable | Not applicable |
| Pinnipeds (in air) | Cell 13 | Cell 14 | Cell 15 |
| Sound Pressure Level | 109 dB _{peak} re: 20 μPa (flat) | see Tables 12 & 13 in Southall et al., 2007 | see Tables 22 & 23 in Southall et al., 2007 |
| Sound Exposure Level | 100 dB re: (20 μPa) ² -s (M _{pa}) | Not applicable | Not applicable |

For all other sound types (which are the majority), Southall et al. (2007) did not propose explicit threshold criteria, for the reasons of context-dependence and other complexities in the nature of behavioral responses and available literature described above. It was concluded that significant behavioral effects would likely occur at exposure levels below those required for TTS and PTS, but that simple step-function thresholds for behavior (such as the historical NMFS values) were simply inconsistent with the best available science. While an overarching exposure level approach for behavior as seems reasonable for injury is perhaps more convenient from an assessment standpoint, the underlying reasons behind the type and magnitude of behavioral response involve a multitude of factors and require a multivariate assessment method to adequately describe.

To begin addressing some of these issues Southall et al. (2007) derived a severity scaling to attempt for the first time to put some reasonable bounds on the likely significance of observed responses, highlighting the importance of responses with the potential to affect vital rates and survivorship (as in NRC, 2005). An ordinal ranking of behavioral response severity (see Table 4 in Southall et al., 2007) was developed, the intent being to delineate behaviors that are relatively minor and/or brief from those

considered more likely to affect these vital rates. The observed behavioral responses in all 10 conditions for multiple pulses and continuous noise for each of the five functional hearing groups were reviewed in detail, and individual responses were assessed according to this severity scaling and measured or reasonably estimated exposure levels. An example of this severity scaling of the observed behavioral literature in one of these conditions (low-frequency cetaceans exposed to impulse noise, predominantly airguns) that may be particularly relevant to this assessment is shown in **Table H-5**. Blank cells in this table indicate the lack of measured responses for these received sound levels and response categories; an overarching conclusion of Southall et al. (2007) was the striking lack of data in most exposure conditions for marine mammals.

This severity scaling, as evident in **Table H-5**, did not reveal broadly applicable patterns of response in most cases – i.e., where no response occurs below some specific received level and a high probability of response occurs above some point (as step-functions would presume). Certain observations were made, including the behavioral context-dependence of response for different received levels in migrating bowhead whales and the particular sensitivity of harbor porpoises both in field and laboratory experiments. But the primary advances made in the Southall et al. (2007) criteria in terms of behavioral response were to very clearly demonstrate that step-function thresholds for response using a single received level and no other considerations related to behavioral context are overly simplistic and outdated and to develop at least a qualitative means of addressing behavioral response severity issues.

Table H-5

Southall et al. (2007) Assessment of Individual Behavioral Responses of Low-Frequency Cetaceans to Multiple-Pulse Exposure for Various Received Levels

(Individual observations are weighted to account for statistical considerations, and source data are indicated by parenthetical subscript: Malme et al. (1983)¹; Malme et al. (1984)²; Richardson et al. (1986)³; Ljungblad et al. (1988)⁴; Todd et al. (1996)⁵; McCauley et al. (1998)⁶; Richardson et al. (1999)⁷; and Miller et al. (2005)⁸

| Response Score | Received Exposure Level (dB _{RMS} re: 1μPa) | | | | | | | | | | | |
|----------------|--|------------|-------------|---------------|---------------|----------------|-------------|-------------|------------------|--------------------|-------------|-------------|
| | 80 to <90 | 90 to <100 | 100 to <110 | 110 to <120 | 120 to <130 | 130 to <140 | 140 to <150 | 150 to <160 | 160 to <170 | 170 to <180 | 180 to <190 | 190 to <200 |
| 9 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 7 | | | | | | | | | | 1 (6) | | |
| 6 | | | | 9.5 (3,7) | 47.4 (3,7) | 2.2 (3,7) | 1.4 (4) | 2 (1,2) | 5.5 (1,2,4,6) | 9.3 (1,2,4,6,8) | | |
| 5 | | | | | 1 (3,7) | | 1 (4) | 1 (1,2) | | | | |
| 4 | | | | | | | | | | | | |
| 3 | | | | | | | | | 1 (1,2) | 1 (1,2) | | |
| 2 | | | | | | | | | | | | |
| 1 | | | | 5 (3,7) | 6 (3,7) | 1 (3,7) | 2 (1,2) | 3 (5) | | | | |
| 0 | | | | 59.8 (3,7) | 17.7 (3,7) | 1.1 (3,7,8) | 0.1 (8) | 0.1 (8) | 6.8 (1,2,8) | 6.3 (1,2,8) | | |

Clearly, the Southall et al. (2007) criteria for behavior are a starting point to develop a rudimentary framework in moving toward a more multivariate and biologically-meaningful way of assessing the type and magnitude of behavioral responses of marine mammals to noise than historical thresholds. As evidenced by the absence of data in many exposure level and response types above, significant data gaps exist in almost all areas, and many of the available studies lack key information about the nature of

exposure in which behavioral responses were observed (which is why many studies were excluded from the Southall et al. [2007] analysis). This is an active area of research, and subsequent studies (some described above) have begun to report additional information on background noise, various exposure metrics, and behavioral contexts.

Broad application of the Southall et al. (2007) criteria for both injury and behavior has been relatively slow in evolving, in part due to the increased complexity of the recommendations over the previous simplistic approaches, such as step-functions used by NMFS. However, NMFS has used exposure criteria consistent with the Southall et al. (2007) thresholds for injury from sound exposure for assessing potential impacts of Navy active sonar operations (*Federal Register*, 2009a,b) for a host of species, including large whales and pinnipeds. In fact, these regulations actually include higher exposure values for certain species for which higher TTS onset values were directly measured than the more conservative values used in Southall et al. (2007). Additionally, recent NMFS regulations (*Federal Register*, 2009a,b) have also begun to use a more graduated dose-function based approach to behavioral response rather than the historical step-function thresholds. NMFS is preparing acoustic exposure guidelines that are expected to increasingly consider the increased complexity and context-dependence of responses of marine mammals to sound.

6. ASSESSMENT OF HEARING INFORMATION FOR SPECIES/GROUPS IN THE AREA OF INTEREST

Specific sound sources that will be used in G&G exploration activities off the U.S. East Coast, as discussed in **Chapter 3** of the Programmatic EIS, include both impulsive (e.g., 2D and 3D seismic exploration surveys using conventional airguns) and continuous noise sources such as side-scan sonars, sediment sampling, electromagnetic surveys, and various vessel activities.

Most of the marine mammals likely to be present in the Area of Interest (AOI), as discussed in Programmatic EIS **Chapter 4.2.2**, are cetaceans, with some pinnipeds possibly present at very low densities in the northern extent of the area and manatees potentially present in southern, near-coastal waters. For some of these species (e.g., bottlenose dolphins), relatively good information exists about hearing and behavioral responses to some types of sounds (e.g., Nowacek et al., 2001), though not particularly for seismic exploration specifically. For most of the mid-frequency cetacean species, including the endangered sperm whale, the injury criteria proposed by Southall et al. (2007) and general conclusions on behavioral response would be expected to be applicable; direct recent information on behavioral responses in sperm whales to seismic airguns are available as well (e.g., Miller et al., 2009).

For West Indian manatees, direct measurements of hearing are available (Gerstein et al., 1999; Mann et al., 2005), as well as responses to vessel presence and noise (Nowacek et al., 2004a). From the perspective of hearing injury, the use of pinniped exposure criteria from the Southall et al. (2007) criteria would seem reasonable, as described above. These animals are generally very coastal-oriented, which would likely mean they would encounter G&G activities only in nearshore waters.

For the endangered mysticetes that occur in the area (north Atlantic right whale, blue whale, fin whale, humpback whale, and sei whale), as for all low-frequency cetaceans, no direct information regarding hearing is available. As described above, the Southall et al., 2007 exposure criteria for injury are based on assumptions and extrapolations from mid-frequency cetacean data that may need to be reassessed to some degree based on the subsequent measurements of lower onset TTS levels in bottlenose dolphins within their range of best hearing sensitivity (Finneran and Schlundt, 2010). In terms of behavioral response, substantial effort has been made and data are available for impulse noise (seismic airguns specifically) for mysticetes, though not for all of the species present in the AOI. Nowacek et al. (2004b) showed that north Atlantic right whales may be particularly responsive to alarm-like non-impulsive noise in controlled exposure studies. Similarly and more recently, Southall et al. (2011) demonstrated behavioral responses, and an apparent context-dependence in response based on behavioral state, in some blue and fin whales exposed to simulated sonar sounds off the coast of California. The fact that many of the mysticetes in the AOI may be engaged in migratory behavior during the course of operations, the increased sensitivity of some other mysticetes (e.g., bowhead and gray whales) during migrations should be considered in assessing potential responses of species where no direct data on responses to certain sound types (airguns) are available (e.g., blue, fin, and sei whales).

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